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UNUSUAL EVENTS IN NEUTRINO TELESCOPES: SIGNATURES OF NEW PHYSICS[1]

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A class of physical phenomena outside the framework of the perturbatively treated Standard Model of electroweak and strong interactions gives rise to characteristic signatures in neutrino telescopes. In essence, the signature is a large energy deposition in the neighborhood of the telescope, giving rise to large and concentrated Cherenkov light emission, and in some cases, to energetic muon bundles.

1 Introduction

Despite the fact that the Standard Model of electroweak and strong interactions is in a very good agreement with presently available experimental data, the general situation concerning the model is unsatisfactory. There are several reasons for making such a statement. Here are a few.

- One has very little understanding of the mechanism of the breaking of the electroweak symmetry: the Higgs boson has yet to be found. Moreover, there are strong reasons to believe that the theory based on an elementary Higgs field is internally inconsistent.
- We understand very little about the structure of the theory outside the framework of perturbation theory. One is virtually certain that perturbation theory is badly divergent, hence it is useless in the strong coupling region. Consequently, our understanding of important phenomena, like quark

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confinement is extremely limited. (Lattice approximations do contain a hint that quantum chromodynamics indeed confines quarks and gluons. However, quantitative results are still unavailable, in part due to the enormity of the computational problem and, in part, due to theoretical questions connected with the continuum limit of the lattice approximation.

- There are some interesting, non–perturbative phenomena within the framework of the electroweak theory, such as the violation of the *sum* of baryon and lepton numbers, as predicted by 't Hooft, ref. [1], which have received much attention lately. In particular, Ringwald and his collaborators conjectured that if such a process is accompanied by a multiple production of gauge bosons (Z and W), one may reach observable levels of cross sections, see, *e.g.* [2] for a recent review. If observed, such phenomena would shed light on the properties of the ground state of the theory (the vacuum) and, hence, it would be very interesting to observe them.

  However, it is to be emphasized that, so far, the calculations have been extremely unreliable; in fact, one's knowledge of the magnitude of the cross sections involved is both meager and shaky.

In addition to the reasons just mentioned, one feels uneasy about a theory which contains *nineteen* input parameters. (If neutrinos are massive, the number of input parameters is larger still.) Despite the various schemes proposed (grand unified theories, composite models, strings *etc.*) to remedy this situation, very little real progress has been made during the last decade. This is due, in part, to the fact that one cannot make controllable approximations to the theories just mentioned.

There is little doubt that observing a signature of any of the phenomena alluded to above would be of great importance and it would contribute significantly to our understanding of the physics at energy scales above the currently reachable ones (of the order of 100 GeV at the level of quarks and leptons).

In view of theoretical difficulties just mentioned, we'll take a cautious approach: we'll try to extract some salient features of the unreliable calculations, in the hope that those are sufficiently robust and are largely independent of the details of the models. Then, we'll investigate the measurable consequences these phenomena in a neutrino telescope.

2 Common Features of Some Post Standard Model Scenarios

Most scenarios conjectured to step beyond the Standard Model have an important feature in common, *viz.* an excess production of hadrons under unexpected

circumstances. (Most supersymmetric models do not belong to this category.) Let us illustrate this point on two examples mentioned earlier and on one not yet mentioned.

1. *Preon models.* Even though most proposed preon models have been less than spectacularly successful so far, they may constitute a reasonable step towards reducing the number of arbitrary input parameters in the Standard Model. Typically in any economical preon model, quarks and leptons share at least some preon constituents. As a consequence, at energies exceeding the characteristic scale of the model (say, the energy at which a hypothetical metacolor gauge theory enters its strong coupling regime), in a sense, both leptons and quarks become "schizophrenic": in particular, lepton–quark interactions begin to produce energetic hadrons in the projectile fragmentation regime. Scenarios of this kind and their consequences in UHE neutrino physics have been discussed previously, *cf.* [3, 4, 5] and references quoted therein. It is rather hard to estimate the hadron multiplicity in the initial interaction; however, if QCD can be used as a guide, one expects that about half of the initial energy will go into a hard neutrino or charged lepton and the other half into about 20 or so quark pairs, *cf.* [5] and references quoted there. Thus the total hadronic multiplicity is about 20 or so, carrying about half of the primary energy.

2. *Multiple production of weak gauge bosons.* Strictly speaking, this process is *within* the framework of the Standard Model; however, it is definitely a non–perturbative phenomenon and thus, it is, in a sense, "new physics". Due to the fact that both W and Z decay into hadrons roughly 70% of the time, if multiple W/Z production takes places in a neutrino interaction, one is likely to see, on the average, a large number of hadrons in the initial interaction. As a rough estimate, let us assume that there are 20 weak gauge bosons produced, see *e.g.* [2]. On the average then, about 14 of them decay hadronically; the average multiplicity is of the order of 10, mostly light mesons and a negligible number of baryon pairs. Thus, the initial energy is expected to be distributed among about 200 mesons (not counting the hadronic decay modes of the τ) and some ten or so hard leptons, depending on the (still ill–understood) details of the process.

In both the multi–W production and the compositeness scenarios it is essential to concentrate on ν induced reactions: in any other type of reaction (with the possible exception of a $\gamma\gamma$ collider) the backgrounds are unacceptably high. In both cases, the essential observation is that the estimated cross sections are in the μb range or somewhat smaller; however, several orders of magnitude larger than the neutrino cross sections given by perturbative calculations within the framework of the standard model.

Let us observe that for cross sections of this magnitude and for CMS energies in the multi–TeV range, the effects of nuclear structure (surface absorption, *etc.*)

are entirely negligible. Consequently, the target appears as a gas of nucleons to the projectile; hence the interaction mfp is independent of A. Numerically, one gets:

$$\lambda[\mathrm{g/cm^2}] \approx \frac{1670}{\sigma[\mathrm{mb}]} \tag{1}$$

It follows that, according to eq. 1, a mfp of 4,000 mwe ($\approx 4 \times 10^5 \mathrm{g/cm^2}$) corresponds to a cross section of about 4 μb. Hence, a neutrino incident nearly vertically will produce, on average, the first interaction close to the typical neutrino telescope (DUMAND II or NESTOR). Lower cross sections can be observed at higher zenith angles. Details depend on the density profile surrounding the detector and we shall not discuss this question any further at this time.

3 The Qualitative Appearence of the Underwater Cascade

While details differ in the first two scenarios outlined in the previous Section, in both cases one produces a number of mesons going forward in the CMS — a phenomenon not expected in neutrino induced rections within the framework of the Standard Model and perturbation theory. For all practical purposes, there are no nucleon pairs produced in the initial interaction; most of the mesons produced (about 90 % or so) are light (π, K).

At the relevant energies (several TeV in the LAB system), the hadronic interaction mfp is of the order of 50 g/cm^2. In water, this corresponds to a distance of about 50 cm. This is to be compared with a typical charged meson decay mfp which is of the order of $\gamma \times 8$m. (Here, γ stands for the Lorentz factor of the meson in question.) Hence, *light charged mesons do not decay*: there are no delayed muons in the cascade. The only muons to be found are “prompt” ones, coming from either the primary interaction (in the first scenario in the previous Section) or (mostly) from the deacy of the weak gauge bosons in the second one. (An additional source of prompt muons is the production of mesons containing c and b quarks: it is not clear at present what fraction of those mesons will be; however, one does not expect it to be very high.)

Neutral pions (about $1/3^d$ of all mesons produced) will decay rather than interact: as a consequence, there will be a very substantial electromagnetic (EM) component in the cascade. Most of the EM component will originate from π^0 (and η^0) decay. In the second scenario discussed in the previous Section, there is a small (at the $\approx$ 10% level) prompt EM component originating from the decay of the weak gauge bosons into electrons (and ν_e in the case of the charged gauge bosons). We do not believe that one can realistically expect a distinction between the prompt and delayed parts of the EM components of the cascade

within this century. Hence, we shall concentrate on the EM component arising from π^0 and η^0 decay from now on.

In what follows, we are going to present a quantitative picture of the longitudinal development, based on an approximate casacade theory as outlined in ref. [6].

4 Calculation of the Cascade Development

Due to the large theoretical uncertainties in the primary interaction, we can simplify matters considerably in the casacade calculation. Some of the simplifications introduced have been discussed previously, *cf.* ref. [6]. Below, we briefly summarize the simplifications.

- The majority of mesons produced is a pion; we neglect the production of mesons containing s, c, b and t quarks. (This simplification introduces an error of the order of 15 %.)
- The mesons $\pi^\pm$ do not decay, the interaction rate of any π^0 is negligible compared to its decay. Hence, by charge symmetry, about $2/3^d$ of the mesons participate in the cascade, the remaining ones feed the electromagnetic component.
- There are practically no initial baryons in the casacade and baryon pair production is negligible: one can work with a single component hadronic cascade.
- Photoproduction of mesons is small: the photoproduction cross section is about 1% of the hadronic inelastic one. Hence, the hadronic component develops autonomously, with a negligible feedback from the electromagnetic one.
- As a consequence, the electromagnetic component has a a source (from the process $\pi^0 \to \gamma\gamma$), otherwise, it develops on its own.
- Approximation A is adequate for both components since we are mainly interested in the high energy component of the cascade.

We have shown in ref. [6] that even atmospheric cascades can be treated reasonably accurately (at a level of error about 35% or so at the highest energies) under these simplifications. Due to the absence of nucleons, the treatment should work better in the present case.

With the simplifications mentioned above, the cascade theory is a linear one to a high degree of accuracy. As a consequence, it is not important to specify the multiplicity in the initial interaction precisely; multiplicities in the cascade

scale linearly with the initial one. (Linearity breaks down at the lowest energies considered: low energy mesons produce fewer secondaries than high enrgy ones and the cascade stops.) Similarly, since, *on the average* the portion of the initial neutrino energy going into meson production is distributed uniformly among the mesons, the average meson energy at the beginning of the cascade is given by the simple formula:

$$E_1 = \frac{\kappa E_\nu}{\langle N_0 \rangle}, \tag{2}$$

where κ stands for the inelasticity (we estimate it to be about 1/2) and $\langle N_0 \rangle$ is the average multiplicity in the first interaction. Later on, we plot the evolution of a cascade by taking $\kappa E_\nu = 10^{17}$eV and (in order to study the the effect of the nonlinearity at "low" energies) we plotted the cases $\langle N_0 \rangle = 20$ and $\langle N_0 \rangle = 5$, respectively.

4.1 The Hadronic Component

We assume the validity of Feynman scaling. (The validity of this approximation has been discussed in some detail in ref. [6].) In the diffusion approximation and neglecting decay, the cascade equation for the hadronic component reads:

$$\frac{\partial H\left(E, x\right)}{\partial x} = -H\left(E, x\right) + \int_E^\infty \frac{dE'}{E} F\left(\frac{E}{E'}\right) H\left(E', x\right) \tag{3}$$

Here x stands for the thickness measured in units of the hadronic interaction mfp. The fragmentation function, $F(z)$ is taken to be of the form:

$$F\left(z\right) = C z^{-1+\epsilon} \left(1 - z\right)^3 \Theta\left(1 - z\right). \tag{4}$$

The normalization constant, C and the infrared regulator, ϵ are introduced in order to satisfy the constraints:

$$\int dz F = 1$$

and

$$\int \frac{dz}{z} F = \langle N_h \rangle,$$

$\langle N_h \rangle$ being the average multiplicity in a hadronic interaction. (We chose $\langle N_h \rangle =$ 30.) Most results which follow are rather insensitive to the precise value of ϵ.

We solve this equation for a monochromatic initial spectrum in order to be able to follow the longitudinal development of the cascade in some detail. The initial condition is:

$$H\left(E, 0\right) = \langle N_0 \rangle \delta\left(E - \kappa E_\nu\right) \tag{5}$$

The solution is obtained by means of the iterative procedure described in ref. [6]. The evolution is cut off when the CMS energy in the interactions drops below $\sqrt{s} = 30$ GeV.

Figure 1: Longitudinal distribution of hadrons; initial multiplicity, $N_0 = 5$

In the following Figures we exhibit the result for the initial energy and multiplicities described above. We are interested in the integral spectrum of hadrons and of the EM component.

Figure 1 displays the longitudinal structure of the cascades for a low initial multiplicity $N_0 = 5$. The two curves correspond to energies $E > 10$ GeV (upper curve) and $E > 100$ GeV (lower curve), respectively.

Figure 2: Longitudinal distribution of hadrons; initial multiplicity, $N_0 = 20$

As expected, the hadronic distribution is quite narrow in x and, similarly in real space. For all practical purposes, the energetic hadrons are concentrated within a space of about 6 m in water. Figure 2 contains the same information as the previous one, but with an initial multiplicity, $N_0 = 20$.

The shower profiles are quite similar for $E > 10\,\mathrm{GeV}$, provided one scales the curves appropriately. Higher energies are more affected by a larger initial multiplicity, due to the fact that, on the average, higher multiplicities lower the initial emergy per particle in the primary interaction.

4.2 The Electromagnetic Component

This component is treated within the framework of Approximation A. The electromagnetic cascade equations are inhomogeneous, the source term for photons, $S(E,\xi)$ being given by

$$S\left(E,\xi\right) = \frac{2}{3} H\left(2E,\rho\xi\right). \tag{6}$$

Figure 3: The longitudinal evolution of the electron – photon component of the cascade. The abscissa is the absorber depth in units of the radiation length, x_r.

Here ξ stands for the distance measured in units of the radiation length (X_0) and ρ is a conversion factor between the hadronic interaction mfp and and X_0. Due to the fact that water is very nearly incompressible, ρ is a constant to a very good approximation, $\rho \approx 0.4$.

Apart form the initial stages of the electromagnetic cascade, the number of electrons and positrons is nearly the same as that of the photons, with a slight photon excess due to the source term.

The solution of the cascade equations with a source term is a staright forward one, once the retarded Green function is found. The latter is best determined by means of an iterative procedure, similar to the one described in ref. [6]; we shall not repeat the description here.

In the following we do not distinguish between the photon and electron–positron components; within the accuracy of the calculation, there is no significant difference between them. In Fig. 3 we plot the longitudinal evolution of the electromagnetic cascade for particles of energy $E > 10$ GeV. (A typical water Cherenkov detector is nearly 100% efficient above such an energy.)

We plotted the evolution for one primary energy and initial multiplicity only: this is sufficient to illustrate the qualitative features. (For a lower initial multiplicity, the shower maximum occurs further down along the cascade, but the number of particle at maximum is higher.) The overall longitudinal size of the electromagnetic component is comparable to the hadronic one (about 6 m); however, the electromagnetic component peaks at ≈ 4 m after the hadronic one. It is worth investigating whether the two separate peaks in energy deposition are observable: if so, this would give rise to a well–recognizable signature in neutrino telescopes of events of this type.

5 Discussion

The estimates described here suggest that neutrino telescopes may play an important role in particle physics in discovering phenomena beyond the Standard Model. The search strategy in a neutrino telescope *with* directional capability (*e.g.* NESTOR) is to scan the range of zenith angles available and serach for large energy deposition within the span of a few meters. Once such events are found, knowing the direction of incidence of the primary allows one to estimate the cross section of the primary interaction. Even without being able to tell the direction of incidence (*i.e.* without the ability to distinguish between zenith angles larger and smaller than 90^o), one can gain useful information: it is hard to think about processes in the cross section range between a few μbarns and the Standard Model neutrino cross section with a large energy deposition in a small volume.

In the previous considerations it was implicitly assumed that after the primary interaction, the evolution of the cascade follows Standard Model physics. While such an assumption is somewhat *ad hoc*, probably it can be justified by arguing that at currently available energies at accelerators the Standard Model is in excellent agreement with the data. Assuming that the primary event creates a sufficiently high number of secondaries, one expects that already the first generation of secondaries will have insufficient energy in order to deviate significantly in its behavior from the Standard model.

Assuming optimistically that "anomalous" events of the kind described here will be found, one can speculate whether one will be able to distinguish between the scenarios sketched before. While we cannot overemphasize the large theoretical uncertainties, one may, nevertheless, see a few potential differences:

- In the multi – W/Z production scheme, the initial interaction tends to produce a substantial number of electrons and muons. As a consequence, the electromagnetic component of the cascade starts right at the primary interaction rather than being separated by a few hadronic mfp–s from it. Also, one expects a muon multiplicity averaging perhaps three or four, appearing in the form of (almost) collinear muon bundles.

- By contrast, in the scheme of composite models (equally beset by theoretical difficulties), due to the fact that most incident neutrinos are expected to be ν_μ, probably, one has *one* very energetic muon emerging from the primary interaction and otherwise hardly any other muons being present.

It is amusing (and perhaps relevant) to remark that the description of at least one event roughly fitting the characteristics of an anomalous event outlined here has been published in the literature, see [7]. It may be interesting to examine the record of other underground detectors for the occurrence of similar events.

Clearly, more work on this subject is needed — both by theorists and experimentalists: it is a very interesting challenge. This century began by the discoveries of what we call now the fundamental elements of modern physics — the discovery of cosmic rays by Victor Hess was among them. Not only did Hess' discovery lead to a number of important discoveries in the emerging science of elementary particle physics, it also contributed substantially to our understanding of the Universe we are living in. It would be quite interesting and pleasing if, by the turn of this century, cosmic ray physics rose to a renewed prominence by the joint effort of particle physicists and astrophysicists.

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